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Estimating carbon stock in lowland Papua New Guinean forest – low density of large trees results in lower than global average carbon stock.

Running Title: PNG forest biomass lower than global mean

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Abstract

Papua New Guinean forests (PNG), sequestering up to 3% of global forest carbon, are a focus of climate change mitigation initiatives yet few field-based studies have quantified forest biomass and carbon for lowland PNG forest. We provide an estimate for the 10,770 hectare Wanang Conservation Area (WCA) to investigate effect of calculation methodology and choice of allometric equation on estimates of above ground live biomass (AGLB) and carbon. We estimated AGLB and carbon from 43 nested plots at the WCA. Our biomass estimate of 292.2 Mg AGLB ha^{-1} (95% CI 233.4-350.6) and carbon at 137.3 $MgCha^{-1}$ (95% CI 109.8-164.8) is higher than most estimates for PNG but lower than mean global estimates for tropical forest. Calculation method and choice of allometric model do not significantly influence mean biomass estimates, however the most recently calibrated allometric equation generates estimates 13% higher for lower 95% confidence intervals of mean biomass than previous allometric models – a value often used as a conservative estimate of biomass. Although large trees at WCA (>70 cm DBH) accounted for 1/5 total biomass their density was lower than that seen in SE Asian and Australia forests. Lower density of large trees accounts for lower above-ground live biomass than in neighbouring forests - as large trees contribute disproportionately to forest biomass. Reduced frequency of larger trees at WCA is explained by the lack of diversity of large dipterocarp species common to neighboring SE Asian forests and, potentially, higher rates of local disturbance dynamics. PNG is susceptible to the El Niño Southern Oscillation (ENSO) extreme drought events to which large trees are particularly sensitive and, with still over 20% carbon in large trees, differential mortality under increasing ENSO drought stress raises the risk of PNG forest switching from carbon sink to source with reduced long term carbon storage capacity.

Introduction

High rates of tropical deforestation and forest degradation contribute substantially to anthropogenic climate change, with recent estimates of their contribution to total atmospheric greenhouse gases ranging from 12% (van der Werf *et al.* 2009) to 20% (Gibbs and Herold 2007). The largest sources of greenhouse gas emissions in most tropical countries, such as Papua New Guinea, are associated with forest loss and degradation (Shearman *et al.* 2009). The tropical forests of PNG have become a focus of climate change mitigation initiatives due to their large capacity for carbon, with 2.5-3% of global stocks (Baccini *et al.* 2012; Saatchi *et al.* 2011). PNG could benefit substantially from mechanisms that reward conservation of forest carbon, such as proposed reduced emissions from avoided deforestation and degradation (i.e. the UN-REDD programme www.un-redd.org). REDD aims to create financial value for the carbon stored in forests and generate incentives for developing countries to reduce emissions from forested lands. However, the first step to initiating any such mechanism is accurate accounting of carbon stock within forest systems.

The most direct way to estimate the largest carbon pool, associated with the living biomass of trees, is based on harvesting, drying and weighing all trees in a given area. The dried biomass is then converted to carbon by taking half of the biomass weight (Westlake 1966). This is extremely expensive and destructive to undertake beyond the local scale. Scaling up global datasets for destructively harvested forests has resulted in the development of sets of allometric equations relating forest carbon stock to easily measured characteristics such as diameter at breast height (DBH) and tree height (Brown 1997; Chave *et al.* 2005; Chave *et al.* 2014; Ferry *et al.* 2010).

Today, allometric regression equations are key to the estimation of carbon stock density and fundamental to calculations in estimating change in carbon stocks for REDD+ projects

(Pearson 2005; VCS 2013). Generating locally-derived allometric equations for tropical forest is time-consuming, logistically challenging, costly and rarely represents the full range of sizes and species found at a particular site (Gibbs *et al.* 2007). As an alternative generic pan-tropical models have been developed from global databases of destructively sampled trees (Chave *et al.* 2005) and updated over time (Chave *et al.* 2014). This has provided a readily available, low tech tool that is widely understood and that can be applied at relatively low cost, as fieldwork is the major cost component. Generic relationships between forest carbon stock and DBH and height have improved with the increase in global datasets from destructively harvested samples but they may not be appropriate for all regions and it has been challenging to produce globally consistent results (Anitha *et al.* 2015; Gibbs *et al.* 2007; Pelletier *et al.* 2013). At any site local biogeography, environmental conditions and historical exploitation of forest resources can have a significant influence on growth characteristics that may fail to be captured by generic equations. The uncertainty of the accuracy of these generic equations at the project site level has been queried (Pelletier *et al.* 2013), and there are challenges in adoption of standardised, comparable measures following updated calibration of these equations. In many cases these field based estimates are also in use to calibrate remote sensing methodologies that can provide assessments of forest stock at higher temporal and greater spatial scale (Brown *et al.* 2005; Gibbs *et al.* 2007), but this requires confidence in field assessments.

Although the dataset on which allometric models is expanding, samples from Papua New Guinea (PNG) are underrepresented, even in the latest calibration of allometric equations (Chave *et al.* 2014). For accurate carbon accounting the influence of allometric model choice on final biomass and carbon estimate is important as it also influences field survey designs. To date many biomass and carbon estimates are based on one of the allometric models developed by Chave et al. (2005) that allow estimation of biomass based on allometric relationships with tree measurements of DBH, and optionally, height. The latest allometric model, calibrated on an extended dataset (Chave *et al.* 2014), requires both DBH and tree height measurements. It is important to evaluate the influence of the new allometric model on biomass estimation to avoid bias in assessment of carbon.

Another weakness of current estimates of above-ground biomass estimates for PNG is that they have generally been generated from studies investigating other aspects of forest ecology, so are based on a range of plot sizes and replicates that can add uncertainty to in-country forest biomass estimation (Bryan *et al.* 2011). Sampling designs range from a destructively sampled single 20 m^2 plot (Grubb and Edwards 1982), hectare plots generated for forestry studies (Bryan *et al.* 2010a) to a single, large 50 hectare plot within the Wanang Conservation Area, the same forest block as our study (Vincent *et al.* 2015). Apart from our study, only one previous estimate of biomass (Venter 2015; Venter *et al.* 2015) is based on application of Land Use, Land-Use Change and Forestry (LULUCF) protocols (Pearson 2005) designed to assess carbon stock and typically applied within the existing voluntary carbon market (VCS 2013). These protocols aim to minimise artefacts from survey design such as spatial autocorrelation, high likely in extrapolating forest carbon estimates from a single 50 hectare plot (Vincent *et al.* 2015) or lack of randomisation, possible when using existing forestry datasets potentially biased to highly productive forest sites (Bryan *et al.* 2011; Bryan *et al.* 2010a; Fox *et al.* 2010). To date we have widely ranging estimates for above ground live biomass for lowland PNG forests from 193 Mg AGLB ha^{-1} (Bryan *et al.* 2010b) to 604.1 Mg AGLB ha^{-1} (Venter 2015) although it is unclear how much of this difference is due to choice of method used to calculate biomass.

This study contributes to meeting the urgent need for further studies within PNG to provide an accurate estimate for forest biomass and carbon. We collected field data from lowland PNG forest to provide an estimate for the 10,770 hectare Wanang Conservation Area in the Madang region of PNG by following protocols for carbon stock assessment (Pearson

2005) and aim to improve accuracy by applying local tree species-specific density values. We also investigate the influence of calculation method and allometric model choice on biomass estimates and compare our results to global, regional and other PNG estimates in an attempt to explain the results in the context of the local biogeographical and disturbance history of PNG forests.

Materials and Methods

Study Site and sample points

The Wanang Conservation Area (WCA) lies within the Middle Ramu region of Madang province, Papua New Guinea (PNG). The WCA covers an area of 10,770 hectares of primary lowland rainforest classified as tropical, wet, mixed evergreen forest (Paijmans 1976). Soils are a shifting mosaic of entisols, inceptisols and alfisols and climate is aseasonal, with an average temperature of 25.8˚C and annual precipitation of 4000 mm, with over 125 mm rainfall per month (Vincent *et al.* 2015). The topography is composed of ridges and valleys with our sample sites ranging from 90 m asl to 213 m asl.

A randomly allocated fixed grid design of 43 plots separated by 1 km was designed in ArcGIS 10.02 and overlain on a map of the Wanang Conservation Area to establish sample plots (Figure 1). Fieldwork took place from 3rd October to December 16th 2014. In the field, plots were located by GPS (Garmin GPSmap 62S). At each plot we established permanent square, nested sample plots with dimensions shown in Figure 2. In the field, plot locations were marked with a hand held GPS and a metal stake embedded in the ground at the south west corner. Corners of the plot and subplot were marked by PVC pipes. All trees greater than 5cm DBH were measured at a height of 1.3m in the 0.04 ha subplot with only trees of DBH>50cm recorded in the extended 0.05 ha plot. A ladder was used to measure DBH at 1.3m above buttress roots of large trees. Standardised adjustments to DBH measurement, outlined in

Pearson (2005) were applied to unusual trunk structures such as bifurcating and sloping trees. Each tree was tagged and a full species identification was recorded where possible, with local names or classification by genus or family used when full identification was not feasible. The size classes of trees sampled within each nested plot are given in Figure 2. In addition to DBH and tree species, height was estimated using a laser rangefinder (Leica DISTO D5).

Wood density

Where available, we obtained values for wood specific gravity from a destructively sampled plot at Wanang (Whitfeld 2011) which provided site specific data for 132 of the species. Subsequently we used publically available datasets for species (World Agroforestry Centre Wood Density database - 46 species; Chave *et al.* 2005 – 17 species). For species at Wanang with no published data for density we assumed phylogenetic consistency and applied average genus level wood specific gravities (available from the online datasets) for 142 species. If no genus level data was available we used family average data (7 species) and where no family data was available (2 species) we used the average of the Wanang species wood densities from our study.

Above-ground live biomass and carbon estimation

Above-ground live biomass (AGLB) was estimated and compared using equations [1] and [2] for wet forest stands developed by Chave et al (2005). Equation [1] includes diameter and height, whereas equation [2] is based on diameter at breast height alone. We compare these results with the updated generic allometric equation that incorporates both height and diameter using equation [3] (Chave *et al.* 2014).

$$(AGB)_{est} = 0.0776 * (\rho D^2 H)^{0.940} \quad \text{[Equation 1]}$$

$$(AGB)_{est} = \rho * exp\,(-1.239 + 1.980 \ln(D) + 0.207\,(\ln(D))^2 - 0.0281(\ln(D))^3 \quad \text{[Equation 2]}$$

$$(AGB)_{est} = 0.0673 * (\rho D^2 H)^{0.976} \quad \text{[Equation 3]}$$

where ρ is wood specific density (g/cm^3), D is diameter at breast height (cm) and H is tree height (m). Above ground biomass was estimated for all trees (excluding those > 50 cm DBH) in the 0.04 hectare subplots then scaled to AGLB per hectare before adding biomass for all trees in both plots > 50 cm DBH, also scaled to a hectare. The sum provides an estimate of AGLB per hectare from each sample plot. We converted to estimated carbon mass using the conversion factor of 0.5, to convert from AGLB to carbon (Westlake 1966). Means and 95% confidence intervals were estimated for AGLB and carbon. We then compared estimates generated by the range of allometric equations for PNG forest. The influence of environmental variables on AGLB was explored using multiple regression in the R Statistical package (R Development Core Team 2012). For normality and homoscedasticity AGLB was log-transformed and significant relationships between slope, aspect, altitude, latitude and longitude explored at the alpha = 0.05 significance level.

Calculations for comparison against other carbon estimates from PNG

A range of methods have been applied to estimation of above ground biomass from the relatively few previous field plot studies in Papua New Guinea (Bryan *et al.* 2010b; Fox *et al.* 2010; Grubb and Edwards 1982; Venter 2015; Venter *et al.* 2015; Vincent *et al.* 2015). As choice of calculation methodology or allometric model linking DBH and tree height to biomass may influence estimates we applied the same biomass calculation methodology from other studies to our datasets for comparison. To compare with values generated by Fox et al. (2010)

we applied allometric equation 1 (Chave *et al.* 2005) to estimate biomass from height and DBH measurements. Although they used an average wood density figure of 0.477 for all their stems we continued to apply species-specific densities. To best parallel the approach taken by Bryan et al. (2010b) we estimated palm and pandanus volume using a cylindrical coefficient ($V_p=A_pH_p$), and a paraboloid coefficient for trees ($V_t=0.5A_tH_t$), where V is the stem volume, A is the basal area and H is the height of the stem. We multiplied individual stem volumes by species specific densities and summed the data to estimate total above ground biomass. This estimate also provides a useful calibration of the estimates provided by the allometric equations. Venter et al. (2015) applied a similar methodology to ours using nested replicate plots and equation 1 to estimate above ground biomass, but included deadwood in their biomass totals. Finally we compared our estimate of above ground biomass (and carbon) with that by Vincent et al. (2015) from a 50 hectare plot sample within the Wanang conservation area. Their methodology differed in that all stems > 1cm DBH were used, whereas we used only > 5cm DBH values. They showed that the 1 – 10 cm size class contributed 7.2% to total AGLB so to best compare with their estimate we first calculated biomass from our dataset based on stems > 10cm in 0.04 ha sample plots using equation 2 (Chave *et al.* 2005) and subsequently added the 7.2% contribution from the 1 – 10 cm size class.

Results

Sampling generated a total of 2129 individual stems from a total area of 1.72 hectares. Of these we identified 337 species, 157 genera and 66 families of tree. The majority of biomass (74.1%) is associated with the 10 – 70 cm size class. The smaller size class of 5 – 10 cm accounts for 4.3%. Large trees (>70 cm DHB) were rare in the sample plots, however this size category accounted for over a fifth of total above ground biomass from some 4 trees per hectare (Table 1). Average wood density of our dataset was 0.556 gcm^{-3}. The top 10 tree species, in terms of biomass, contributed 54.9% of total AGLB (Table 2). The greatest contributor to AGLB (18.4 %) in the plots, *Pometia pinnata*, was also the most abundant species with the second most abundant species, *Mastixiodendron pachyclados*, contributing 9.3% to biomass. A single, large individual of *Ficus crassiramea* contributed the third highest above ground biomass – highlighting the disproportionate importance of large trees in carbon sequestration.

Multiple regression showed no significant influence on biomass for combined environmental variables of altitude, slope, aspect, latitude and longitude ($p = 0.3$). We also found no significant relationship between large trees (> 70 cm DBH) and slope.

Estimates of AGLB density for the Wanang Conservation Area

There was no significant difference in mean estimates of above-ground living biomass for the WCA for estimates that ranged from 249.3 Mg AGLB ha^{-1} to 292.2 Mg AGLB ha^{-1} ($F(3,168) = 0.39$, $p = 0.76$) using the range of allometric equations and the methodology applied by Vincent et al. (2015) (Table 3). It is however worth noting that using the latest allometric equation resulted in a 13% increase in lower 95% confidence interval compared to the lowest estimate. This value is often employed as a conservative estimate of carbon stock.

No significant difference was seen for estimates of carbon density for the WCA from the application of the full range of calculation methodologies ($F(6,258) = 0.48$, $p = 0.82$) applied to other studies in PNG (Table 4; Figure 4).

The heterogeneity of AGLB throughout the landscape is illustrated in Figure 3, with biomass estimates from replicate plots ranging from 45.6 Mg AGLB ha^{-1} to 979.2 Mg AGLB ha^{-1}. The two plots with very high relative biomass contain very large trees.

Carbon Estimates for the Wanang Conservation Area

Using the most recently calibrated allometric equation, we estimate mean biomass for the 10,770 hectare Wanang Conservation Area at 3,147,221 tonnes - that equates to 1,479,194 tonnes of carbon (Table 5) (Precision: 95% confidence interval of half-width of 20% of the mean).

Discussion

The large storage capacity for carbon in PNG forests means they are likely to play a key role in climate change mitigation initiatives. The few existing field studies (Bryan *et al.* 2011; Bryan *et al.* 2010a; b; Fox *et al.* 2011; Fox *et al.* 2010; Grubb and Edwards 1982; Venter 2015; Venter *et al.* 2015; Vincent *et al.* 2015) that have assessed forest biomass and carbon for lowland forest provide widely ranging estimates, from 193 Mg AGLB ha^{-1} (Bryan *et al.* 2010b) to 604 Mg AGLB ha^{-1} (Venter 2015). Of these published estimates only one used experimental design protocols designed specifically to assess biomass and carbon (Venter 2015), with other studies using datasets collected from sampling programmes focused on forestry (Bryan *et al.* 2011; Bryan *et al.* 2010a; b; Fox *et al.* 2011; Fox *et al.* 2010) or forest ecology (Vincent *et al.* 2015). Our study is based on sampling protocols for assessment of carbon (VCS 2013), incorporating species-specific densities, that allows us to provide a robust estimate of biomass and carbon for lowland PNG forest at the Wanang Conservation Area of 292.2 Mg AGLB ha^{-1} (137.3 MgCha^{-1}). Our value is lower than the global average for tropical forests due to low densities of large trees in lowland PNG forest at Wanang - possibly a result of disturbance and biogeographical history of this forest system. We also show that choice of allometric equations and calculation methodology does not significantly influence biomass and carbon estimates. This suggests that field surveys using only DBH in plot measurement could save time/resources allowing increased replication in forest such as the WCA with high levels of spatial heterogeneity in AGLB to provide a conservative estimate of biomass and carbon stock.

However, the range of allometric equations do generate different estimates for the lower confidence intervals for mean carbon density (Figure 4), often used as a conservative estimate of carbon density. Using the most recently calibrated equation (Chave *et al.* 2014), based on DBH and height measurements, can substantially raise the lower 95% confidence interval for mean carbon density by 13% compared to use of allometric equations based simply on DBH measurements (Chave *et al.* 2005).

Comparing our results to Global estimates

Applying the most recently calibrated allometric model (Chave *et al.* 2014) to our dataset we found that PNG lowland forest at the Wanang Conservation Area, with 292.2 Mg AGLB ha^{-1} (95% CI 233.4 – 350.6), has a lower biomass value than the global mean for tropical rainforests (373.7 Mg AGLB ha^{-1}) and lower values than regional rainforest biomass estimates for Australia (418.5 Mg AGLB ha^{-1}, Bradford et al., 2014; 619.4 Mg AGLB ha^{-1} Murphy et al., 2013), Asia (393.2 Mg AGLB ha^{-1}) and Africa (393.3 Mg AGLB ha^{-1}) (Slik et al 2013). However our value is higher than mean estimates for the Americas (287.9 Mg AGLB ha^{-1}, Slik et al., 2013).

In comparison to neighbouring SE Asian and Australian lowland forest the WCA in PNG has significantly lower above-ground live biomass. The major contributor to this trend appears to be a reduced density of large trees (over 70 cm DBH), that contribute disproportionately to forest biomass (Slik *et al.* 2013) (Figure 5). At our study site large trees contributed only 21.6% to biomass compared to average of 39.1% for SE Asian forest, and 44.51% for African forests (Slik *et al.* 2013). Our sampling protocol appears robust in having accurately captured the density of these larger trees, as a 50 hectare sample plot within the same forest also identified large tree density of 4 – 5 per hectare (Vincent *et al.* 2015). Only 10% (4 of 42 SE Asian forest sites) had a similar or lower densities of large trees to those seen from our sample at Wanang (Slik *et al.* 2013). Many Asian forest systems are dominated by dipterocarps that grow to extremely large stature and would significantly influence biomass stock, however these species are relatively poorly represented in PNG, to the east of Wallace's line (Morley 1998). Low densities of large trees does also suggest that local disturbance dynamics might be of higher intensity in these forests, resulting in greater spatial variability in structure and a higher proportion of biomass represented by small trees. This is supported by that fact that PNG forests at Wanang do show significant differences to other tropical forest types, for example the contribution of small trees to biomass is higher than the global average of 5%, at 7.2% (Vincent *et al.* 2015), although this is a naturally a result of lower contributions from large trees. The lower density of larger trees, and higher biomass associated with small trees seen at Wanang is likely a function of biogeographical history and combinations of local disturbance mechanisms that include soil type and climate. Much of lowland PNG is formed of uplifted oceanic sediments that established an unstable series of ridges (Loffler 1977). This, under the influence of high rainfall events, rapidly erodes soil, undercutting and destabilising establishment of larger trees, although we found no significant correlation between slope and density of large trees. In conjunction climate is likely to play a significant role in shaping these forests and in future carbon dynamics. PNG is highly susceptible to the El Niño–Southern Oscillation (ENSO) that results in irregular drought events due to periodical variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean (Cobon *et al.* 2016). The impact of drought and large-scale wildfires in PNG due to the 1997/1998 ENSO event caused widespread tree mortality, with net carbon emissions due to degradation continuing for up to 10 years afterwards (Fox *et al.* 2011). Large trees are particularly sensitive to drought events as they suffer extreme hydrological challenges in transporting water against gravity, and pathway-associated resistance, to leaves in the canopy that are under lower water availability and higher evaporative demand. Drought-induced tree mortality has been estimated at 5-17% in nearby

Borneo with a cumulative water deficit (MCWD) greater than 150mm (Nakagawa *et al.* 2000; Phillips *et al.* 2010), with the most susceptible trees being the largest (Bennett *et al.* 2015). With its susceptibility to ENSO events, previous drought events are also likely to have played a role in maintaining low densities of large trees at Wanang (Salinger and Lefale 2005). It is worth noting that the growth rate of small trees increases with drought (possibly due to increased solar radiation reaching the understory) and may contribute to the observation by Vincent et al (2015) of higher biomass associated with smaller trees.

In spite of challenges in ENSO prediction, periodic drought stress is expected for PNG with large trees likely to suffer most, with drought-driven feedbacks to the carbon cycle. With over 1/5th carbon stored in large trees (Table 1) this could reduce the capacity of increasingly seasonal forest to store carbon. The differential mortality of large trees increases risk of threshold switching from carbon sink to source for PNG forest, reducing long term carbon storage capacity (Bennett *et al.* 2015; Bennett *et al.* 1998).

The comparatively high biomass estimates for lowland forest observed by Venter et al. (2015) in Morombe Province to the South East of our site point to another possibility by suggesting that human activity has contributed to lower densities of larger trees seen in the WCA, with larger trees historically targeted for construction purposes, or that forest remains in recovery following long-term forest gardening activity. There is little information on human impacts to forest at the WCA, however there is increasing evidence of prehistoric impact to forest both globally (Bush *et al.* 2015; Fraser *et al.* 2014) and in PNG (Haberle 2007) suggesting that lower densities of large trees might have result from past human impacts.

Comparison of carbon estimate with those from other PNG studies

Making comparisons with existing published data on AGLB and carbon within PNG is complicated by a number of factors that include the minimum DBH size surveyed in field plots, wood density values applied and the choice of allometric equation or calculation used in biomass estimation (Chave *et al.* 2005; Chave *et al.* 2014). To understand the influence of calculation methods on final biomass estimates we first applied calculation methods used in other studies to our own dataset and show that calculation method, and choice of allometric equation does not significantly influence final mean estimates of biomass for the WCA.

A comparison of our estimate of AGLB using the latest allometric equation with other published values for PNG can be seen in Figure 6. The first estimate of forest carbon (155 $MgCha^{-1}$) was generated in a study by Grubb and Edwards (1982) based on the destructive sampling of 0.24 hectares of Eastern highland mid-montane forest at 2500 masl. Subsequently, carbon estimates from ten 1-hectare permanent sample plots maintained by the Papua New Guinea Forest Research Institute generated an estimate of 106.3 ± 16.2 $MgCha^{-1}$ for stems >10 cm diameter (Fox *et al.* 2010). They used allometric equation 1 (Chave *et al.* 2005) to estimate biomass from height and DBH measurements and an average wood density figure of 0.477 for all stems. Using similar calculations on our own dataset, our estimate of carbon for lowland forest at Wanang was not significantly different, at 110.43 ± 21.65 $MgCha^{-1}$. The only difference in calculation was that we applied species-specific density data to each tree (generating an average density of 0.556 gcm^{-3}).

Bryan et al. (2010b) collected field data from unlogged primary forest sites using a plotless measurement of basal area, volume, and biomass (Bitterlich 1947). They estimated and summed individual tree and palm volumes, multiplying by species-specific densities to attain above ground biomass. We applied identical calculations to estimate biomass from our field dataset generating an estimate of 245.43 Mg AGLB ha^{-1} ± 78.30 (95% CI) and 137.71 Mg C ha^{-1} ± 39.15 (95% CI) for carbon. This compares with their mean unlogged above ground live biomass values from their two study regions of 192.96 ± 8.70 Mg AGLB ha^{-1} (mean ± 95% CI) and 252.92 ± 13.73 Mg AGLB ha^{-1} (mean ± 95% CI). Our estimates for AGLB of 256.20 Mg

AGLB ha^{-1} ± 53.2 (mean ± 95% CI), using the methodology of Venter (2015), are almost half of their biomass estimates of 600.4 ± 110.4 Mg AGB ha^{-1} for lowland forest between 50 – 150 m above sea level. Their biomass estimate is the highest from the existing PNG datasets.

It is reassuring to note that estimates we generated for the WCA using the methods of Bryan et al (2010b), that calculate individual bole volumes, are similar to our results from calculations using allometric equations, however our confidence intervals for the mean are still rather large. It is also reassuring for global carbon budgeting that our estimate of 292.2 Mg ha^{-1} is very close to the average above-ground biomass estimates for PNG generated by Saatchi et al. (2011) of 294 – 306 $Mgha^{-1}$ AGLB. This provides some level of confidence that globally calibrated allometric equations predict AGLB for PNG lowland forest. We still recommend, as do Chave et al (2014), the development of locally derived diameter–height relationships to minimize bias for PNG lowland forests as they are underrepresented in allometric model calibration, as are the larger tree diameter classes (Anitha *et al.* 2015).

Our estimates for the Wanang Conservation Area

Our estimate of 292.2 Mg AGLB ha^{-1} (95% CI 233.6 – 350.8 Mg AGLB ha^{-1}) using smaller plots distributed throughout the Wanang Conservation Area of 10,000 hectares, and applying the most recently calibrated allometric equation (Chave *et al.* 2014) for above ground biomass, is significantly higher than the previous estimate for the Wanang Conservation area of 210 (95% CI 191.1 – 226.9) Mg AGLB ha^{-1} obtained from a 50 hectare plot (Vincent *et al.* 2015). High levels of heterogeneity resulted in our estimate falling short of the minimum recommended precision target established by the voluntary carbon standard of 15% for 90% confidence (UNFCCC 2010; VCS 2013). Based on our data, 51 carbon plots of 0.04 hectares are the minimum sampling effort for a robust estimate of biomass and carbon stock. Potential exists however to combine our data with that from the existing 50 hectare plot, through the development of a mixed plot statistical design, to improve precision of AGLB and carbon estimates. In a recent study Grussu et al. (2016) recommend an optimum plot size of 0.2 ha for 155 replicates for 95% confidence within 5% of the mean for PNG lowland forest systems.

Our total carbon estimate for 10,770 ha of the WCA (1,552,347 MgC) demonstrates the importance of the conservation area in terms of carbon sequestration and the potential for the community to engage with mechanisms such as REDD. Also, it is important to recognise the high tree species diversity of these forests (>300 species across 66 families) that provides unique added biodiversity value.

Conclusion

In this study we applied standardised sampling protocols for assessment of carbon (VCS 2013) in 10,770 hectares of lowland forest in PNG. We incorporated locally derived data on species-specific densities where available to provide an estimate of 292.2 Mg AGLB ha^{-1} for biomass and 137.3 $MgCha^{-1}$ which is lower than global averages for tropical lowland forests. This is due to low density of large trees that contribute disproportionately to carbon stock, in turn probably due to biogeographical history and high levels of disturbance in PNG forests. The susceptibility of large trees to ENSO drought events requires further investigation as this could impact long term storage of carbon in these forest systems. We show that choice of allometric equation does not significantly influence biomass and carbon estimates suggesting that methods relying on DBH measurement alone might free resources to allow increased levels of replication to improve biomass estimates in forests with high levels of AGLB heterogeneity. This study contributes important information on forest carbon pools in PNG to aid participation in climate mitigation initiatives by providing transparency to baseline information for the Wanang Conservation Area, highlighting its importance and potential as a priority REDD site.

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Tables

Table 1. Distribution of stems and biomass across size classes for the 0.04 hectare sample plots.

	Number of Stems	AGLB (Mg ha^{-1})	% AGLB
5 - 10 cm	701	5.7	4.3%
10 - 70 cm	494	98.5	74.1%
70 + cm	4	28.8	21.6%

Table 2. Top ten tree species ranked on contribution to biomass.

Top 10 Species (Family) **for AGLB**	AGLB (Mg/ha)	% AGLB **per hectare**	Order Vincent et al **50 ha plot** (2015)	Density (Stems/ha)
Pometia pinnata (Sapindaceae)	69.3	18.4	1	42.0
Mastixiodendron pachyclados (Rubiaceae)	34.9	9.3	3	46.0
Ficus crassiramea (Moraceae)	20.7	5.5		0.6
Celtis latifolia (Cannabaceae)	19.1	5.1	4	31.6
Intsia bijuga (Fabaceae)	16.5	4.4	2	3.4
Maranthes corymbosa (Chrysobalanaceae)	13.6	3.6		2.9
Canarium indicum (Burseraceae)	10.0	2.6		7.5
Sloanea sogerensis (Elaeocarpaceae)	8.7	2.3		2.3
Celtis philippensis (Cannabaceae)	7.0	1.9		3.4
Pterocarpus indicus (Fabaceae)	7.0	1.8	10	5.2

Table 3. Estimates for above ground biomass and carbon ($Mgha^{-1}$) with 95% confidence limits for the Wanang Conservation Area

	AGLB (Mg/ha)	ABG 95% CI (Mg/ha)	Carbon (Mg/ha)	Carbon 95% CI Mg/ha
Chave (2005) equation 1	272.5	55.4	128.1	26.0
Chave (2005) equation 2	249.3	42.9	117.2	20.1
Chave (2014) equation 3	292.2	58.6	137.3	27.5
Protocol of Vincent et al (2015)	262.0	71.5	127.3	35.7

Table 4. Biomass and carbon estimates from other studies of PNG lowland forest with estimates for carbon at the Wanang Conservation Area when applying their methods to our dataset.

Biomass estimates for PNG lowland forest (Mgha^{-1} Above-ground live biomass)	*Carbon (MgCha^{-1})*	*Carbon estimate for Wanang Conservation Area applying calculations from reference study to our dataset*	*Calculation summary for:* *1. Equation* *2. Variables* *3. Tree densities*	*Reference*
310	*155*	*na*	*na*	*(Grubb and Edwards 1982)*
212.6 ± 32.4	106.3 ± 16.2	110.43 ± 21.6	*1. Chave equation 1* *2. DBH, height* *3. Average wood density for all stems*	*(Fox et al. 2010)*
192.96 ± 8.70	*96.5* ± 4.3	137.71 ± 39.1	*1. Estimated tree and palm volumes* *2. DBH, height* *3. Species-specific densities*	*(Bryan et al. 2010b)*

252.92 ± 13.73	*126.5* ± 6.9	137.71 ± 39.1	*As above*	*(Bryan et al. 2010b)*
210 (191.1 - 226.9)	*105* *(95.5 – 113.4)*	127.3 ± 35.7	*1. Chave equation 2* *2. DBH* *3. Species-specific densities*	*(Vincent et al. 2015)*
(Altitude 50m) *604* ± 110.4	*300* ± 55.2	128.1 ± 26.0	*1. Chave equation 1* *2. DBH, height* *3. Species-specific densities*	*(Venter 2015)*

Table 5. Mean and 95% confidence interval estimates for total above ground live biomass (AGLB) and above ground carbon for the Wanang Conservation Area using the range of allometric equations and methods applied to a 50 hectare plot within the same forest area (Vincent *et al.* 2015).

Equation	**AGLB (Mg)**	**Lower 95% AGLB interval (Mg)**	**Upper 95% AGLB interval (Mg)**	**Carbon (Mg)**	**Lower 95% Carbon Interval (Mg)**	**Upper 95% Carbon Interval (Mg)**
Chave (2005) equation 1	2620780	2124324	3117236	1231766	998432	1465101
Chave (2005) equation 2	1627160	1352208	1902111	764765	635538	893992
Chave (2014) equation 3	3302865	2644677	3961054	1552347	1242998	1861695
Vincent et al. (2015)	1566193	1290692	1841695	736111	606625	865597

Figures

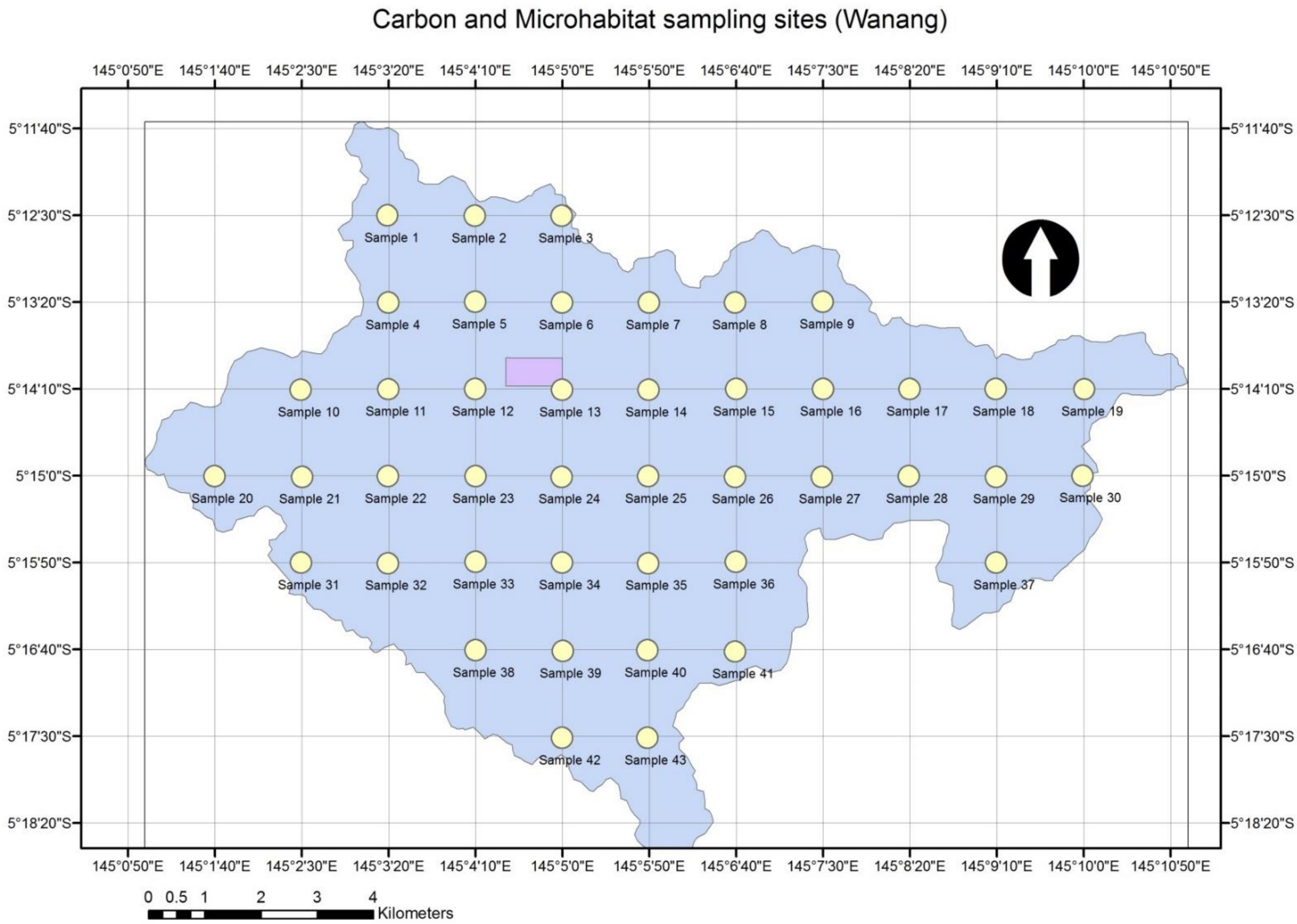

Figure 1. Biomass sampling plots within the Wanang Conservation Area, Madang Province, Papua New Guinea.

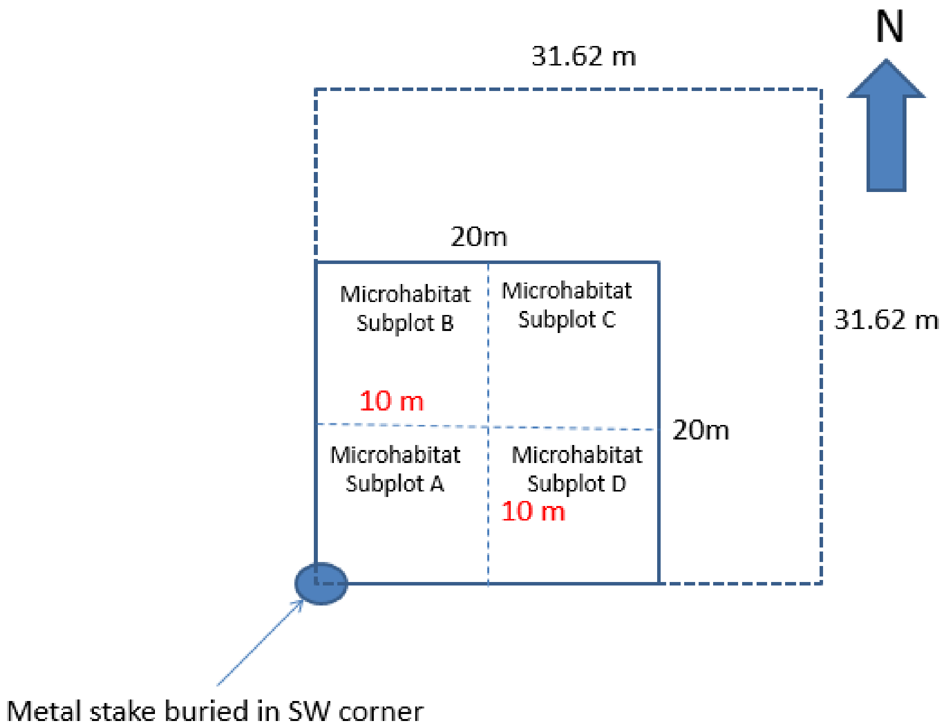

Figure 2. Nested plot dimensions – trees > 5cm DBH (Diameter at Breast Height) measured in 20m x 20m plot and only trees > 50cm DBH in larger plot (31.62m x 31.62m).

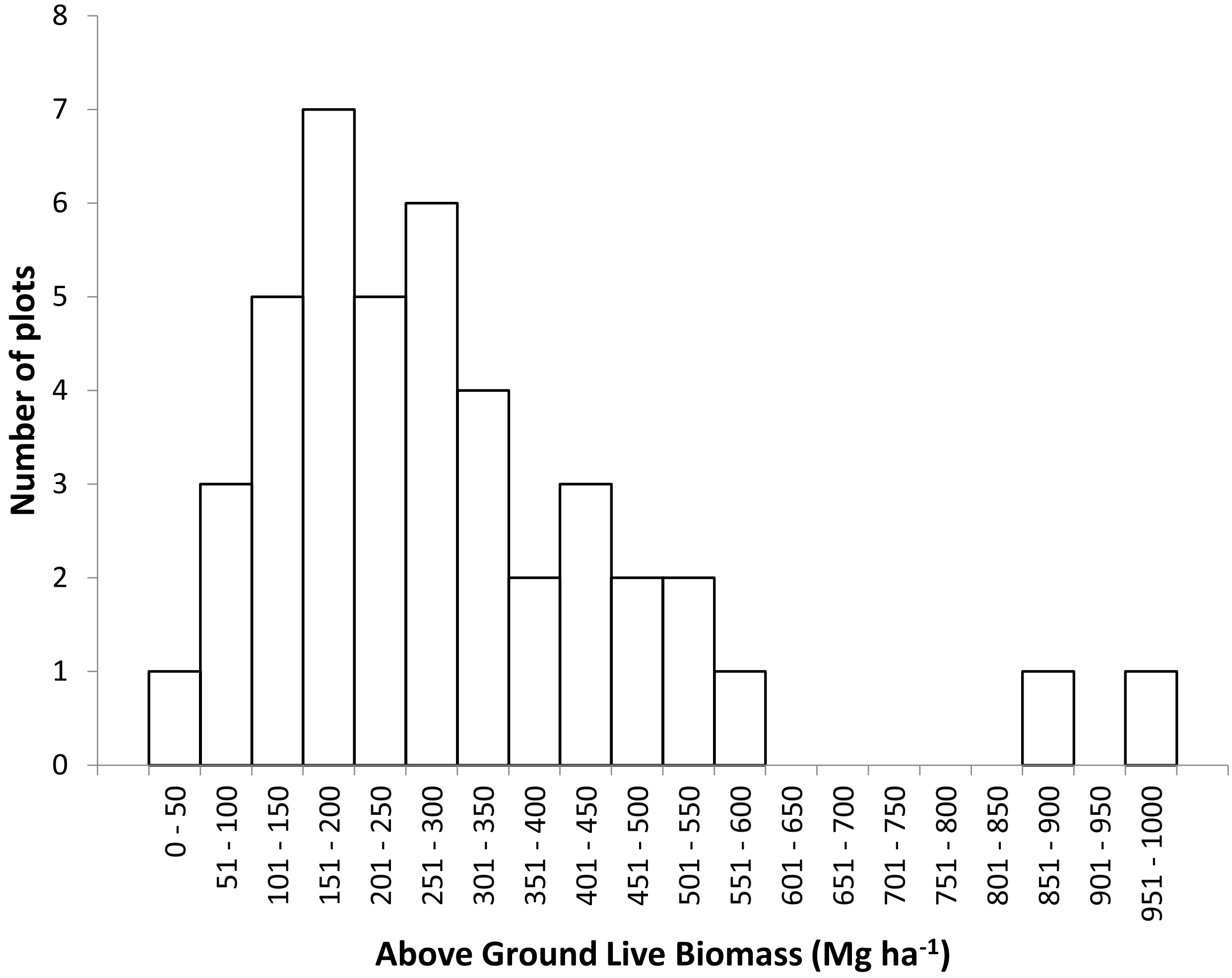

Figure 3. Histogram illustrating high level of heterogeneity in above ground live biomass samples from 0.04 ha plot samples from the Wanang Conservation Area.

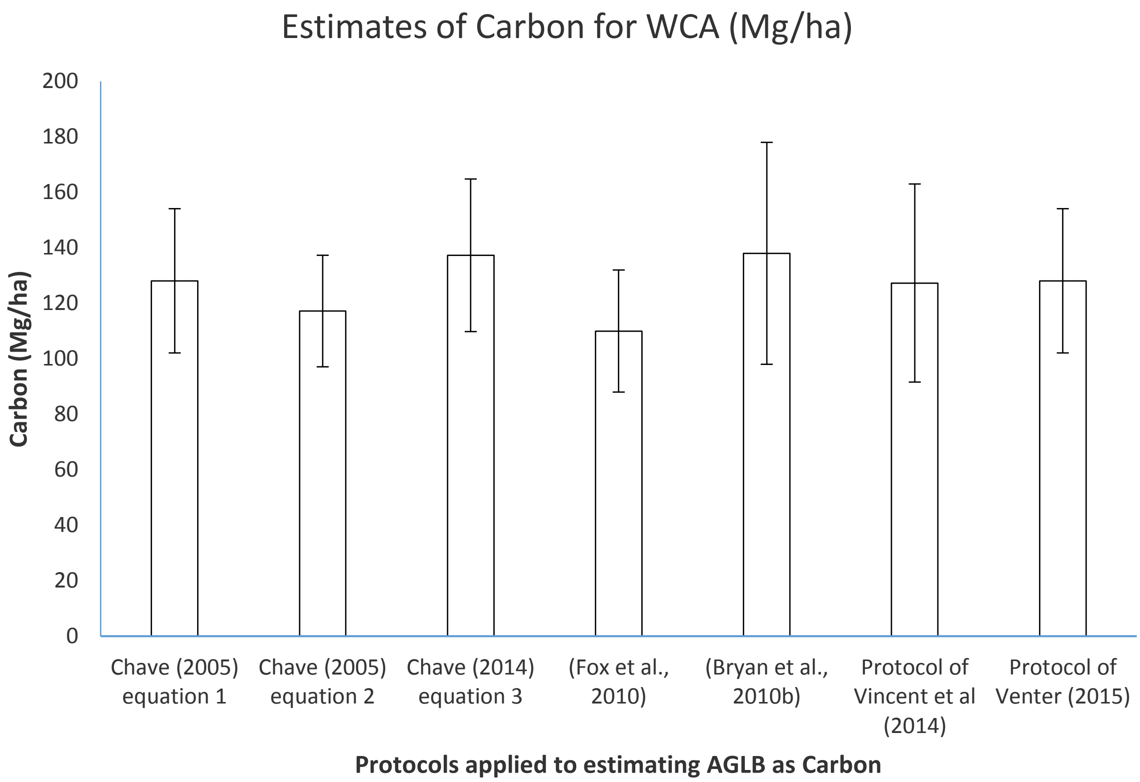

Figure 4. Comparison of mean above-ground live biomass (as carbon) with 95% confidence intervals when applying calculation protocols from other studies to our dataset.

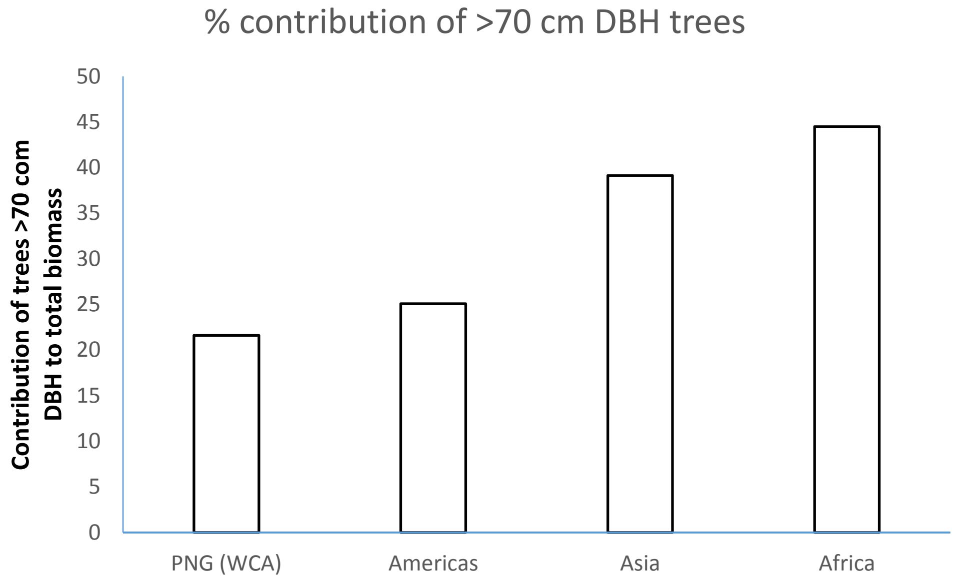

Figure 5. Comparing contribution to above ground live biomass per hectare of trees >70cm diameter at breast height from the Wanang Conservation Area (PNG) to averages for lowland forest in America, Asia and Africa

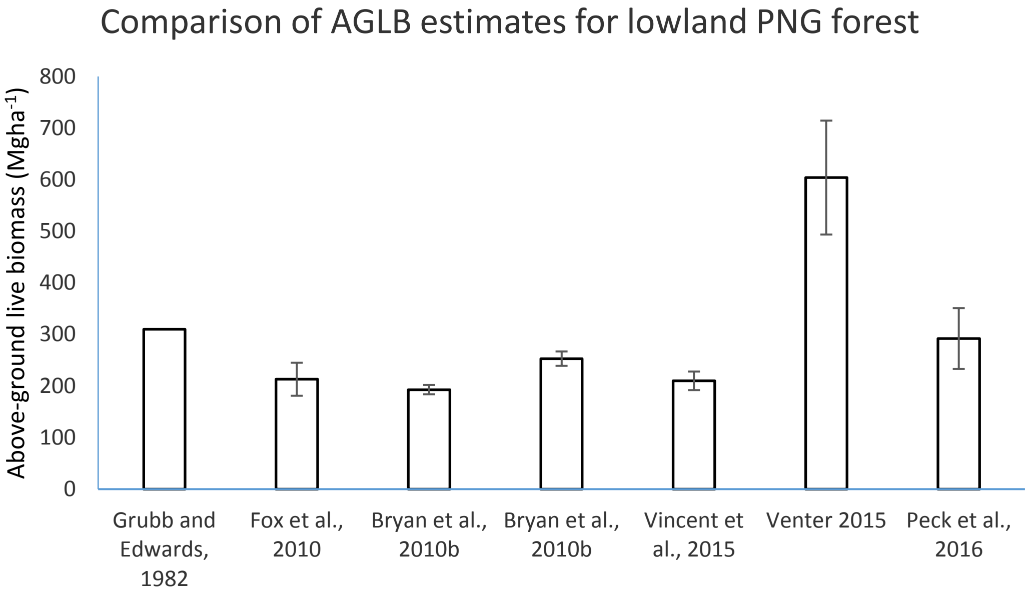

Figure 6. Comparison of above-ground live biomass (mean and 95% confidence intervals) from other studies in PNG to our results in this paper for the Wanang Conservation Area (Peck et al 2016).